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Probing the Charm Yukawa Coupling in Higgs + Charm Production

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We propose a new method to determine the coupling of the Higgs boson to charm quarks, via Higgs production in association with a charm-tagged jet: $pp \rightarrow hc$. As a first estimate, we find that at the LHC with 3000 fb^{-1} it should be possible to derive a constraint of order one, relative to the SM value of the charm Yukawa coupling. As a byproduct of this analysis, we present an estimate of the exclusive $pp \rightarrow hD^{(*)}$ electroweak cross section. Within the SM, the latter turns out to be not accessible at the LHC even in the high-luminosity phase.

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I. INTRODUCTION

While the Yukawa couplings of the heavy third-generation fermions to the Higgs boson can be measured at the LHC with a $\mathcal{O}(10\%)$ accuracy, see e.g. Ref. [1], constraining the diagonal Yukawa couplings of the second (first) generation quarks at a level close to the Standard Model (SM) expectation is very challenging. An interesting possibility, especially for the second generation, is trying to indirectly access these couplings via the radiative decays $h \rightarrow \mathcal{M} + \gamma(Z)$ [2–5], where \mathcal{M} is a quarkonium state.¹ As pointed out in Ref. [8], the exclusive $h \rightarrow \mathcal{M}V$ decays ($V = \gamma, Z, W$) may indeed be accessible at the SM level at the LHC and represent a precious source of information on physics beyond the SM. In the specific case of the charm Yukawa coupling (Y_c), it should be possible to obtain bounds 2–3 times larger than the SM value in the high-luminosity (HL) phase of the LHC [9]. These constraints are driven mainly by the direct search for $h \rightarrow c\bar{c}$ and, to a smaller extent, also by the indirect sensitivity via $h \rightarrow J/\Psi\gamma$.

In this paper, we propose a new method to measure Y_c by means of Higgs production in association with a charm-tagged jet. A particular advantage of this method, compared to the search for $h \rightarrow c\bar{c}$, lies in the fact that we probe Y_c in production –via the interaction with a charm quark from the abundant gc initial state– allowing to reconstruct the Higgs from its clean decay modes ($h \rightarrow \gamma\gamma$ or $h \rightarrow WW$). This procedure strongly reduces the problem of the non-Higgs background, compared to $h \rightarrow c\bar{c}$. Moreover, requiring a single c -tagged jet in the final state allows to adopt high-purity (and low-efficiency) c -tag algorithms in order to reduce background (mainly

from b -quark jets), compared to the case of two c -tagged jets (as in $h \rightarrow c\bar{c}$).

Compared to the indirect sensitivity to Y_c in $h \rightarrow J/\Psi\gamma$, our new method has the advantage of being sensitive to Y_c at the tree-level and being based on a process that, after charm- and Higgs-tagging efficiencies, yields $\mathcal{O}(1000)$ signal events at the HL-LHC. For comparison, we recall that $\mathcal{B}(h \rightarrow J/\Psi\gamma \rightarrow \mu^+\mu^-\gamma) \sim 10^{-7}$, corresponding to $\mathcal{O}(10)$ signal events in pp collisions at 14 TeV with 3000 fb^{-1} . The main limiting factor of our approach is the theoretical uncertainty on $\sigma(pp \rightarrow hc)$, as a function of Y_c . This error could be reduced in the future by means of higher-order QCD calculations of the ratio $\sigma(pp \rightarrow hc)/\sigma(pp \rightarrow hb)$ as a function of Y_c and Y_b .

In principle, the production of the Higgs boson in association with a charm jet (or a charm hadron) can also proceed via electroweak interactions, with the charm being produced by a real or virtual W boson. To complement this analysis, and previous studies of exclusive hadronic Higgs decays [2, 3, 5, 8], we present here the first estimate of the electroweak production of the Higgs boson in association with a single D or D^* meson ($q\bar{q} \rightarrow hD^{(*)}$). These processes are insensitive to the charm Yukawa coupling and could have represented a potential background for the extraction of Y_c . We have analyzed them in generic extensions of the SM, along the lines of Ref. [8]. We find that, within the SM, the exclusive electroweak production should not be visible at the LHC, even in the high-luminosity phase. Moreover, we find that these processes are not competitive with the corresponding exclusive Higgs decays ($h \rightarrow \mathcal{M}V$) as far as generic new physics (NP) searches are concerned.

The paper is organized as follows. In Sect. II we introduce the setup to describe Higgs physics with modified Yukawa couplings. The QCD-Yukawa $pp \rightarrow hc$ process and the corresponding extraction of Y_c is discussed in Sect. III. The exclusive electroweak $pp \rightarrow hD^{(*)}$ process is analyzed in Sect. IV. The results are summarized in the Conclusions.

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¹ For indirect bounds on first generation Yukawa couplings see Ref. [6, 7].

II. SETUP

Within the SM the couplings of the physical Higgs boson to the fermions are completely determined in terms of fermion masses. However, in the presence of NP, a misalignment between quark-mass and Yukawa matrices is possible. This can be parametrized in a model-independent way by adding the $D = 6$ operators

$$\mathcal{L}_6^Y = -\frac{1}{v^2} ((\Phi^\dagger \Phi) \bar{q}_L C_u \Phi^c u_R + (\Phi^\dagger \Phi) \bar{q}_L C_d \Phi d_R) \quad (1)$$

to the SM Lagrangian. Here, Φ denotes the Higgs doublet, parametrized in unitary gauge as $\Phi = 1/\sqrt{2}(0, h+v)^T$, where v corresponds to the vacuum expectation value $\langle \Phi \rangle = 1/\sqrt{2}(0, v)^T$, h is the physical Higgs field, and q_L, u_R, d_R are the chiral SM-quark doublet and singlets (all quark fields being 3-vectors in flavor space). Inserting this decomposition of the Higgs doublet into (1) as well as into the SM-like ($D = 4$) Yukawa terms with couplings $\hat{Y}_{\text{SM}}^{u,d}$, we obtain the fermion masses and Higgs couplings in the flavor basis

$$\mathcal{L} \supset -\bar{u}_L \left(\hat{M}^u + \frac{h}{\sqrt{2}} \hat{Y}^u \right) u_R - \bar{d}_L \left(\hat{M}^d + \frac{h}{\sqrt{2}} \hat{Y}^d \right) d_R, \quad (2)$$

where the Yukawa matrix $\hat{Y}^{u,d} = \hat{Y}_{\text{SM}}^{u,d} + \frac{3}{2} C_{u,d}$ and the mass matrix $\hat{M}^{u,d} = \frac{v}{\sqrt{2}} (\hat{Y}_{\text{SM}}^{u,d} + \frac{1}{2} C_{u,d}) = \frac{v}{\sqrt{2}} (\hat{Y}^{u,d} - C_{u,d})$ are independent parameters. After performing a rotation to the mass basis

$$\begin{aligned} \hat{M}^u &= U_L^u M_{\text{diag}}^u U_R^{u\dagger}, \quad M_{\text{diag}}^u = \text{diag}(m_u, m_c, m_t), \\ \hat{M}^d &= U_L^d M_{\text{diag}}^d U_R^{d\dagger}, \quad M_{\text{diag}}^d = \text{diag}(m_d, m_s, m_b), \end{aligned} \quad (3)$$

with $U_L^d = U_L^u V_{\text{CKM}}$, we finally arrive at the couplings of the physical quarks to the Higgs boson $\mathbf{Y}^u = U_L^{u\dagger} \hat{Y}^u U_R^u$, $\mathbf{Y}^d = U_L^{d\dagger} \hat{Y}^d U_R^d$, such that

$$\mathcal{L} \supset -\bar{u}_L \left(M_{\text{diag}}^u + \frac{h}{\sqrt{2}} \mathbf{Y}^u \right) u_R + (u \rightarrow d). \quad (4)$$

Here, we concentrate on possible experimental constraints on the diagonal entry $Y_c \equiv (\mathbf{Y}^u)_{22}$. For convenience, we parametrize the deviations from the SM prediction ($C_u = C_d = 0$) in terms of $\kappa_q \equiv Y_q v / (\sqrt{2} m_q) \neq 1$, which we assume to be real for simplicity.²

III. THE QCD-YUKAWA $pp \rightarrow hc$ PROCESS

We consider the production of a Higgs boson in association with a charm-quark jet. At the LHC, the main

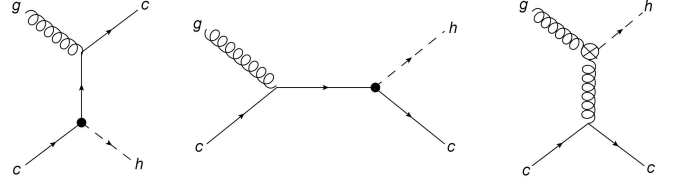


FIG. 1. Diagrams contributing to $pp \rightarrow hc$ at leading order. Black dots correspond to vertices where the Yukawa coupling Y_c enters, while the crossed vertex corresponds to the SM-like top triangle, integrated out.

partonic process inducing this final state is $gc \rightarrow hc$ and the corresponding Feynman diagrams are presented in Figure 1. The charm Yukawa coupling, depicted as a black dot, enters in the first two graphs, that yield a contribution to the amplitude of $O(g_s Y_c)$. The t -channel diagram turns out to be largely dominant. The third diagram is formally of higher order in α_s but is enhanced by the top-quark Yukawa coupling. Here the crossed vertex corresponds to the effective ggh interaction obtained by integrating out the top quark. This diagram yields the contribution to the amplitude that survives in the limit $\kappa_c \rightarrow 0$ (see Table I).

The challenge of the proposed process is to tag the charm-quark jet, as in $h \rightarrow c\bar{c}$. However, as anticipated, it offers some interesting virtues compared to $h \rightarrow c\bar{c}$. In particular, it allows us to fully reconstruct the Higgs boson in a clean decay channel such as $h \rightarrow \gamma\gamma$ or $h \rightarrow WW$, and it requires only a single charm tag. The main drawback is that the process does not vanish in the limit $Y_c \rightarrow 0$ (contrary to $h \rightarrow c\bar{c}$) requiring a good theoretical control on the cross section as a function of Y_c . While a full analysis, including the optimization of the event selection, is beyond the scope of this article, here we just want to examine the potential of the channel by deriving the expected number of signal and background events, based on reasonable efficiency assumptions.

We have calculated the cross section of $pp \rightarrow hc$ at leading order in QCD (including the effective ggh as discussed above) at the LHC with 14 TeV center-of-mass energy for various values of κ_c , employing **MadGraph5** [10], with a tailored model file and **CTEQ6L1** parton distribution functions. Using $m_c(m_Z) = 0.63$ GeV and $m_h = 125$ GeV, for $\kappa_c = 1$ (i.e., the SM) we obtain a cross section of $\sigma(pp \rightarrow hc) = 166.1$ fb, employing the default cuts of $p_T(j) > 20$ GeV, $\eta(j) < 5$, $\Delta R(j_1, j_2) > 0.4$ for all processes considered here. In the following, we focus on the $h \rightarrow \gamma\gamma$ decay channel, with a branching fraction of $\mathcal{B}(h \rightarrow \gamma\gamma) = 0.0023$. This leads to $S_0 = 2292$ events at the HL-LHC with 3000 fb^{-1} , taking into account also the $pp \rightarrow h\bar{c}$ process. Assuming a charm-tagging efficiency of $\epsilon_c = 0.4$ (see e.g. Ref. [9]), we finally end up with $S = \epsilon_c S_0 = 917$ signal events. The different number of events obtained by varying κ_c are reported in Table I.

The main backgrounds to the process studied here are $pp \rightarrow hg$, with the gluon mis-identified as a charm

² In the following we assume the top and bottom Yukawa couplings to be constrained close to their SM values after the high-luminosity LHC run.

κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

TABLE I. Number of Signal events $S(\kappa_c)$ in dependence on the charm-quark Yukawa coupling. See text for details.

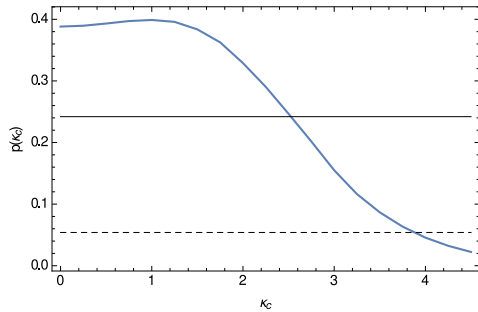


FIG. 2. The expected p -value for a given value of κ_c from the process $pp \rightarrow hc$ at the 14 TeV LHC with 3000 fb^{-1} and a conservative assumption for the theoretical uncertainty. See text for details.

quark, as well as $pp \rightarrow hb$, with the bottom quark being mis-tagged. In the first case, we treat separately the case $pp \rightarrow hc\bar{c}$, where only one charm-quark jet is reconstructed and the case where the gluon produces a light quark jet. The backgrounds feature $\sigma(pp \rightarrow hg) = 12.25 \text{ pb}$, $\sigma(pp \rightarrow hb) = 203 \text{ fb}$, as well as $\sigma(pp \rightarrow hc\bar{c}) = 55 \text{ fb}$. We employ a conservative assumptions for the jet reconstruction efficiency of $1 - \epsilon^{\text{miss}} = 95\%$, as well as $g \rightarrow c$ and $b \rightarrow c$ mis-tag rates of $\epsilon_{g \rightarrow c} = 1\%$ and $\epsilon_{b \rightarrow c} = 30\%$. With these figures we obtain $B = 1705$ background events at 3000 fb^{-1} , leading to $N(\kappa_c = 1) = S(\kappa_c = 1) + B = 2622$ total events. We then assume a statistical error on the total number of events (\sqrt{N}) and a theoretical (relative) error on the signal events of 20%. The latter is deduced by the recent next-to-leading order (NLO) analysis of the Higgs production in association with bottom quarks [11]. Finally, statistical and theoretical error are added in quadrature.³

In the following, we want to examine the expected constraints that can be set on κ_c from the process under consideration. To this purpose, we assume the SM to be true and calculate how many standard deviations $\Delta N(\kappa_c)$ away a prediction $N(\kappa_c)$ is from $N(\kappa_c = 1)$, which is the expected outcome of the experiment. The values of κ_c that lead to a discrepancy of more than n standard deviations are then expected to be excluded at

$n\sigma$. We plot the corresponding p -value, $p(\kappa_c)$, in Figure 2 approximating the Poisson distribution of the number of events by a Gaussian. The 1σ and 2σ equivalents are depicted by the solid and dashed lines, respectively. A conservative estimate for the expected $1-\sigma$ (95% CL) constraint on κ_c is thus obtained as

$$|\kappa_c| < 2.5 \quad (3.9), \quad (5)$$

which lies in the ballpark of the results quoted in [9], where the latter combines ATLAS and CMS to arrive at $2 \times 3000 \text{ fb}^{-1}$ of integrated luminosity.

On the other hand, an improved prediction of the SM cross section $\sigma(pp \rightarrow hc)$, leading to $\delta_{\text{th}} = 10\%$, would strengthen our expected $1-\sigma$ (95% CL) limit to

$$|\kappa_c| < 1.9 \quad (2.6), \quad (6)$$

approaching the SM value of Y_c .

We note that optimized cuts can still increase S/B and in particular lead to an enhanced sensitivity on κ_c . As the statistics at 3000 fb^{-1} is large enough, there are good prospects to still improve the bounds. A corresponding detailed investigation, including detector simulation, is beyond the purpose of this letter and can be performed best by the experimental community.

We further stress that the dominant source of uncertainty, at present, is the theoretical error on $\sigma(pp \rightarrow hc)$. We have indeed checked that the result does not change significantly worsening the $g \rightarrow c$ and $b \rightarrow c$ mis-tag rates to 5% and 40%, respectively. As far as the reliability (and possible reduction) on the theoretical error is concerned, a promising possibility would be a dedicated calculation of $\sigma(pp \rightarrow hc)/\sigma(pp \rightarrow hb)$ at NLO (or NNLO), as a function of Y_c/Y_b , supplemented by measurements of this ratio and $\sigma(pp \rightarrow hb)$ with a combination of normal and inverted b vs. c tags.

IV. THE ELECTROWEAK $pp \rightarrow h\mathcal{M}$ PROCESS

As anticipated in the introduction, the production of the Higgs boson in association with charm can proceed also via electroweak interactions, starting from an initial charm-less $q\bar{q}'$ state ($u\bar{d} \rightarrow hW^{(*)} \rightarrow hc\bar{s}$). The case of an on-shell W producing a charm jet can be discriminated from the QCD-Yukawa process by means of appropriate cuts on the jet momentum. Less obvious is the discrimination in the case of a virtual W^* producing a low-momentum c -jet, or even a single charmed hadron. In the following we estimate in detail the specific case of the single meson production: $pp \rightarrow h\mathcal{M}$, with \mathcal{M} being a charmed meson or a charmonium state.

The leading partonic amplitude within the SM is shown in Fig. 3. Following Refs. [8, 12], we parameterize the quark currents appearing in the initial and final state with arbitrary vector and axial couplings:

$$J_{q,ij}^\mu = \bar{q}^i (g_{V,ij} \gamma^\mu + g_{A,ij} \gamma^\mu \gamma_5) q^j. \quad (7)$$

³ The two dominant backgrounds, $pp \rightarrow hb$ and $pp \rightarrow hg$, can both be directly measured at the LHC with specific tags (inverted b vs. c tag for the former and light-quark-jet tag for the latter) - this is why we do not assign an additional theory error to them.

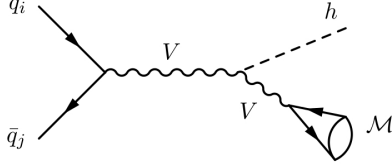


FIG. 3. Diagram contributing to $pp \rightarrow h\mathcal{M}$ at leading order, where $V = W^\pm, Z$.

The matrix element of the current that generates the meson in the final state assumes one of the following structures, depending on the spin of \mathcal{M} :

$$\langle \mathcal{M}(p, \epsilon) | J_q^\nu | 0 \rangle = \frac{1}{2} \begin{cases} g_{\mathcal{P}} f_{\mathcal{P}} p^\nu & \mathcal{M} \equiv \mathcal{P} \\ g_{\mathcal{V}} f_{\mathcal{V}} m_{\mathcal{V}} \epsilon^\nu & \mathcal{M} \equiv \mathcal{V}, \end{cases} \quad (8)$$

where $f_{\mathcal{M}}$ is the meson's decay constant, and $g_{\mathcal{M}}$ encodes the dependence on the coupling to the relevant gauge boson ($g_{\mathcal{P}} = g_{A,ij}$, $g_{\mathcal{V}} = g_{V,ij}$ for a $\langle \bar{q}^j q^i \rangle$ meson).⁴ With this notation, the SM expression for the partonic cross section for the case of a pseudoscalar meson reads

$$\sigma(q\bar{q}' \rightarrow h\mathcal{P})_{\text{SM}}(q^2) = \frac{g_{\mathcal{P}}^2(g_V^2 + g_A^2)f_{\mathcal{P}}^2q^2}{576\pi v^2(q^2 - m_V^2)^2} \lambda^3(q^2), \quad (9)$$

where $V = W^\pm, Z$, and we have suppressed the indices of $g_{A,V}$ for simplicity. The vector case has the same functional form with $\mathcal{P} \rightarrow \mathcal{V}$, up to tiny $\mathcal{O}(m_V^2/m_V^2)$ corrections. In the above expression, q^2 denotes the total momentum of the initial state in the partonic process and

$$\lambda(q^2) = \sqrt{1 - 2 \frac{m_h^2 + m_{\mathcal{M}}^2}{q^2} + \frac{(m_h^2 - m_{\mathcal{M}}^2)^2}{q^4}}. \quad (10)$$

Convoluting the cross sections with the appropriate PDF in the region $130 \leq \sqrt{q^2} \leq 1$ TeV, and assuming an integrated luminosity of 3000 fb^{-1} we obtain the expected number of events for each channel at the HL-LHC. The results, summarized in Table II, show that these processes will not be observable at the SM level, and certainly do not represent a dangerous background for the QCD-Yukawa process discussed in Sect. III.

Given the smallness of the SM signal, it is worth to investigate if these cross sections can be significantly altered beyond the SM. This can be done generalizing the approach of Refs. [8, 12]. The leading (helicity-conserving) transition amplitude can be decomposed in full generality as

$$\mathcal{A}(q\bar{q}' \rightarrow h\mathcal{M}) = -J_q^\mu T_{\mu\nu} \langle \mathcal{M} | J_q^\nu | 0 \rangle. \quad (11)$$

⁴ $g_{V,uu} = \frac{g}{c_W} (\frac{1}{4} - \frac{2}{3}s_W^2)$, $g_{V,dd} = \frac{g}{c_W} (-\frac{1}{4} + \frac{1}{3}s_W^2)$, $g_{A,uu} = -g_{A,dd} = -\frac{g}{4c_W}$, $g_{V,u^i d^j} = -g_{A,u^i d^j} = \frac{g}{2\sqrt{2}} (V_{CKM})_{ij}$

Channel	$m_{\mathcal{M}}$ $f_{\mathcal{M}}$ (MeV)		Events @ HL-LHC	
			Method (a)	Method (b)
η_c	2984	200	0.10	0.08
J/ψ	3100	410	0.08	0.07
D_s^\pm	1968	250	0.48	0.40
$D_s^{*\pm}$	2112	325	0.84	0.69

TABLE II. Expected number of $h\mathcal{M}$ associated production events at HL-LHC (14 TeV and 3000 fb^{-1}) in the energy region $130 \leq \sqrt{q^2} \leq 1$ TeV for representative charmed-meson final states. The results reported under Method (a) are obtained rescaling bin-by-bin the cross section distribution of Drell-Yan processes provided by MadGraph 5 [10]. The computation of Method (b) is performed via numerical convolution of the analytic cross section with the PDF of the MSTW 2008 libraries [13]. Both account only for SM contributions.

To a good accuracy the quark current is conserved ($q_\mu J_q^\mu = 0$), and the tensor $T_{\mu\nu}$ can be decomposed in terms of only four Lorentz structures. Using the same notation as in Ref. [8]:

$$T_{\mu\nu} = f_1(q^2)g_{\mu\nu} + f_2(q^2)p_\mu p_\nu + f_3(q^2)(p \cdot q g_{\mu\nu} - p_\mu q_\nu) + f_4(q^2)\varepsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma, \quad (12)$$

where q_μ is the total momentum of the quark pair in the initial state, and p_μ is the meson momentum ($p^2 = m_{\mathcal{M}}^2$). With these notations the partonic cross section reads

$$\sigma(q\bar{q}' \rightarrow h\mathcal{P})(q^2) = \frac{g_{\mathcal{P}}^2 f_{\mathcal{P}}^2}{2304\pi} (g_V^2 + g_A^2) \times |f_1(q^2) + m_{\mathcal{P}}^2 f_2(q^2)|^2 q^2 \lambda^3(q^2), \quad (13)$$

where, similarly to the SM case, $\sigma(q\bar{q}' \rightarrow h\mathcal{V})$ has the same functional form up to tiny $\mathcal{O}(m_V^2/m_V^2)$ corrections. Neglecting the latter terms, we obtain

$$\frac{\sigma(q\bar{q}' \rightarrow h\mathcal{M})_{\text{BSM}}}{\sigma(q\bar{q}' \rightarrow h\mathcal{M})_{\text{SM}}}(q^2) = \left| \frac{f_1(q^2)}{f_1(q^2)_{\text{SM}}} \right|^2, \quad (14)$$

where $f_1^{\text{SM}}(q^2) \propto 1/(v(q^2 - m_V^2))$ and we disregard potential changes to the fermionic currents. Deviation from the SM are thus induced by possible non-pole-terms (i.e. contact terms) in the form factor $f_1(q^2)$. Within a generic effective-field theory (EFT) approach to Higgs physics (both linear and non-linear EFT), contact terms in $f_1(q^2)$ are generated by dimension-six operators. However, their effect would show-up exactly in the same functional form either in the on-shell associated production ($pp \rightarrow Vh$) or in $h \rightarrow V\mathcal{M}$ decays, that share the same current structure [8, 12]. Since the latter processes can be measured (or at least bounded) to a better accuracy, we conclude that $\sigma(pp \rightarrow h\mathcal{M})$ is not a very sensitive probe of generic extensions of the SM.

V. CONCLUSIONS

In this letter, we proposed a new strategy for the measurement of the Yukawa coupling of the charm quark: the measurement of the production cross section of the Higgs boson in association with a charm jet. A first estimate showed that Y_c could be determined at a level approaching the SM value in this channel, which offers virtues and drawbacks quite different with respect to the $h \rightarrow c\bar{c}$ search. A fully realistic analysis was beyond the scope of the present paper. A more realistic evaluation of the efficiencies is likely to decrease the number of signal events S compared to our naive estimate; however, as we have discussed, the sensitivity on Y_c could even increase with properly designed b and c tag strategies aimed to measure

the background from data and to reduce the theoretical error on the normalization of the cross-section. This first analysis therefore calls for more detailed studies both on the theory and on the experimental side.

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